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A primary standard of attenuation for calibrating microwave components.

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by

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PREFACE

This thesis has been prepared for submission to the United States Naval Postgraduate School as one of the requirements for a degree of Master of Science in Electronics Engineering. The research work, both in the literature and in the laboratory, was done at the Sperry Gyroscope Company, Great Neck, New York, during the period 3 January 1950 to 17 March 1950.

The writer wishes to acknowledge the assistance on innumerable occasions of the engineers and technicians of the Microwave Instruments and Components Development Laboratory and the Microwaves Standards Laboratory of the Sperry Gyroscope Company. In particular, the writer wishes to thank Mr. William Bourke and Mr. Thomas O'Brien for their help in introducing him to the subject of microwave attenuators.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

TABLE OF SYMBOLS AND ABBREVIATIONS

Symbol	
a	Wide dimension of a rectangular waveguide.
a-f	Audio-frequency. (Adjective)
AFC	Automatic frequency control.
α	Attenuation constant of a waveguide.
b	Narrow dimension of a rectangular waveguide.
γ	Propagation constant of a waveguide.
db	Decibel.
e	Napierian base.
i-f	Intermediate-frequency. (Adjective)
k_e	Relative dielectric constant.
log	Logarithm to the base 10.
λ	Wavelength in free space.
λ_c	Cutoff wavelength of a waveguide.
m,n	Mode numbers of a wave in a waveguide.
mc	Megacycles per second.
p_{mn}	Dimensionless constant in equation (5)
P_{in}	Power input to a network.
P_{out}	Power output from a network.
P_1	Maximum available power at the input to a network.
P_2	Maximum power output of a network.
π	3.14159 ...
Q	Quality factor of a coil. (Q = Reactance/Resistance)
r	Radius of a circular waveguide.
r-f	Radio-frequency. (Adjective)
R	Voltage standing-wave ratio.

TABLE OF SYMBOLS AND ABBREVIATIONS
(Cont.)

<u>Symbol</u>

TE	Transverse electric mode in a waveguide.
TM	Transverse magnetic mode in a waveguide.
VTVM	Vacuum-tube voltmeter.
x	Radius of a circular waveguide, or wide dimension of a rectangular waveguide. (Used in equation (8))
z	Axial coordinate of a waveguide.

I. INTRODUCTION

The electronics art has had for some time a requirement for a precise standard of attenuation for radio frequencies. The resistor-type of attenuator used for direct-current and audio-frequency measurements is not suitable for frequencies higher than approximately one-hundred kilocycles per second due to the effects of stray capacitance and lead inductance. Various types of radio-frequency attenuators have been developed mainly for use in controlling the power output of test oscillators, or for limiting the power input to low-level devices. Many of these attenuators have been calibrated, but their accuracy is doubtful because of the lack of a precise standard. The precision attenuator to be described herein was designed to fulfill the requirement for a primary standard.

This thesis is divided into three main parts. Chapter II is concerned with the selection of an attenuator for use as a primary standard. The factors considered in making the choice are discussed, and the waveguide-below-cutoff attenuator is shown to be the only acceptable candidate. The basic principles of the waveguide-below-cutoff attenuator, together with the problems peculiar to it, are discussed in the third chapter. Chapter IV describes the precision waveguide-below-cutoff attenuator designed and built at the Sperry Gyroscope Company, and the tests to which it was put.

II. SELECTION OF A SUITABLE STANDARD OF ATTENUATION

A primary standard, for any type of measurement, is a device whose calibration can be determined from fundamental dimensions, i.e., length, mass and time. The determination of the best means for converting fundamental dimensions into attenuation requires an investigation into the nature of attenuation and the methods by which it can be measured. In addition, the types of attenuators that are available must be studied to show which of them can be calibrated from fundamental dimensions.

1. The nature of attenuation.

As used in electronics, the term <u>attenuation</u> is thought of as a loss of energy, such as the reduction of the power in a signal being propagated along a transmission line, due to series resistance and shunt conductance. Since the loss on a transmission line is an exponential function of the distance along the line, early workers in communications engineering adopted a logarithmic unit, the decibel, as a measure of attenuation. As applied to transmission lines, the decibel was defined by

$$\text{Attenuation} = 10 \log \frac{P_{in}}{P_{out}} \text{ decibels per unit length} \quad (1)$$

where P_{in} and P_{out} are the power levels at the input and output, respectively, of a unit length of line.

Equation (1) cannot be applied to lumped-constant networks without additional restrictions, otherwise ambiguous results are obtained. For example, in the system of Figure 1

the power levels, P_{in} and P_{out}, depend not only on the characteristics of the network but also on the output impedance

Figure 1.

of the generator and the impedance of the load. In order to remove the ambiguity, equation (1) is changed to read

$$\text{Attenuation} = 10 \log \frac{P_1}{P_2} \text{ decibels} \qquad (2)$$

where P_1 is the maximum available power from the generator and P_2 is the maximum power that can be transferred to the load. In other words, equation (2) is valid only when each component is matched to the adjacent components, whether they be networks or transmission lines.

2. Methods for measuring attenuation.

Basically, the measurement of attenuation is the process whereby the loss of signal in a network is translated, by means of the measuring system, into units of attenuation. If the measuring system, or the important components of the system, can be calibrated from the fundamental dimensions, the system (or a component) will be a primary standard of attenuation.

In general, three methods are available for the measurement of attenuation: direct power measurement, the power reflection method, and substitution methods. Of these, the most fundamental is direct power measurement. A value of atten-

uation for a network can be obtained from the power levels at its input and output using equation (2). In practice, the power level at the load would first be determined with the unknown network out of the system. Then, with the unknown network inserted ahead of the load, the load power level would again be measured. These measurements would yield values for P_1 and P_2, respectively, in equation (2).

If the power measuring device could be calibrated from fundamental dimensions, this method would be suitable for use as a primary standard. However, at microwave frequencies, the best commonly available power meters are those employing the thermistor bridge. These instruments, which are calibrated against direct-current or audio-frequency instruments, can measure power levels down to about 10 microwatts with an accuracy of $\pm 10\%$, and are limited to a maximum power level of about 10 milliwatts. This means that the range of attenuation measureable by this method is limited to about 30 decibels with an accuracy of about ± 0.8 decibel.

The power reflection method is based on the fact that the standing-wave ratio due to a poorly matched load can be reduced by inserting a properly matched attenuator ahead of the load. When the load is a short circuit, the attenuation of a component between the standing-wave indicator and the load is given by

$$\text{Attenuation} = 10 \log \frac{R+1}{R-1} \text{ decibels} \qquad (3)$$

where R is the voltage standing-wave ratio. The determination of voltage standing-wave ratio requires the measurement

of the voltage maximum and the voltage minimum along a section of transmission line. For frequencies in the microwave region, the probes, detectors, fittings, etc., on the standing-wave indicator involve such a large number of variables and unknown quantities that a tie-in with fundamental dimensions is virtually impossible. For this reason, the power reflection method is deemed not suitable for use as a primary standard.

In the substitution method, the network whose attenuation is to be measured is compared against a standard attenuator. This requires a circuit in which the unknown and the standard may be inserted between the generator and the load one at a time. Either component, or both, must be variable in order to make an accurate measurement. For example, if the unknown is fixed, it is first connected in the circuit and the generator output is adjusted to give a convenient power level at the load. The standard attenuator is then substituted for the unknown and, with the same generator output, the standard is adjusted until the previous load power is restored. The attenuation of the unknown network is then obtained from the calibration of the standard attenuator. When the unknown is a variable attenuator, it can be calibrated against the standard in a circuit where both attenuators are connected in series between the generator and the load. As one is increased in attenuation, the other is decreased so that the power level at the load is maintained constant. The increments in attenuation of the unknown are then obtained from the known

increments of the standard, obtained from the latter's calibration.

Characteristics of the detector need not be known accurately since the power level at the detector is always the same, but the sensitivity of the indicating system should be such that the power level can be set more accurately than the errors introduced in reading the standard attenuator. If the standard attenuator can be calibrated from fundamental dimensions, the substitution system is admirably suited for use as a primary standard.

Measurement of attenuation by substitution includes three methods: direct substitution, heterodyne substitution and modulation substitution. In the direct substitution method, the standard attenuator must be calibrated at the frequency at which the unknown component operates. A primary standard might be called upon to make a calibration at almost any frequency. This means that the standard must be calibrated (from fundamental dimensions) at all frequencies, or its calibration must be completely independent of frequency, or a very large number of primary standards must be available. Since none of these alternatives is economically attainable, the direct substitution method is ruled out as a practical primary standard system.

The standard attenuator in the heterodyne substitution method operates at some convenient intermediate frequency. The unknown component is placed between the microwave source and a crystal mixer which changes the microwave signal to a lower radio frequency. The standard attenuator is placed

between the converter and the detector. As the unknown is varied, or removed from the system, the standard is varied to maintain a constant power level into the detector. The change in attenuation of the unknown is then equal to the corresponding change in the standard attenuator.

If this method is to be accurate, the output of the mixer must be linearly proportional to the input. The linearity of both diode and crystal mixers has been demonstrated over a range of about 50 decibels. (Gainsborough [3], [4]; Grantham and Freeman [5]) In some cases a pre-amplifier is used in front of the standard intermediate-frequency (i-f) attenuator, in which case the pre-amplifier must also satisfy the requirement of linearity.

The heterodyne method requires that some precaution be taken to prevent or compensate for the drift in frequency of both the microwave source and the local oscillator. Two methods are used for this: the automatic-frequency-control (AFC) method and the sweep-frequency method. In the AFC method, the i-f signal is fed into a discriminator from which an error signal is fed back to the local oscillator. The error signal causes the local oscillator to follow the changes in frequency of the microwave source. A block diagram of the setup using the AFC method is shown in Figure 2.

The sweep-frequency method requires an i-f amplifier with a sharp pass band. The local oscillator is frequency modulated, usually with a sawtooth wave in the audio frequency (a-f) range. The output of the mixer is therefore

frequency modulated about a center frequency near that of the i-f amplifier. As the mixer output signal sweeps past the frequencies that are passed by the i-f amplifier, a pip is generated at the amplifier output which can be read by a sensitive peak-reading voltmeter.

The modulation substitution method is similar to the heterodyne method except that a modulated microwave signal is required. After passing through the unknown component, the microwave signal is demodulated and the a-f signal is fed into a standard a-f attenuator, then into a load and power-level indicator. As the unknown is varied, the standard attenuator is varied to maintain a constant power level into the load. The measuring technique is exactly the same as in the heterodyne system, the only difference being in the equipment. The detector used in demodulating the microwave signal must also satisfy the requirement as to linearity if the measurements are to be accurate. The range of power levels over which most detectors are linear is more restricted (about 30 db) than it is for mixers.

Since either the heterodyne or the modulation substitution method requires only one primary standard for the calibration of components at any frequency, either system is applicable for use as a primary standard, provided that the standard can be calibrated from fundamental dimensions. Of these, the heterodyne substitution method seems to be the better because of its larger useful range.

3. Specifications for a primary standard of attenuation.

In choosing an attenuator for use as a primary standard,

the following characteristics should be investigated:

a. Method of calibration

b. Impedance matching

c. Stability

d. Range of attenuation

e. Precision

f. Frequency sensitivity

The method of calibration is the only factor that determines whether or not a particular attenuator can be used as a primary standard. As for any primary standard, the calibration must be related directly to fundamental dimensions. Any attenuator that does not meet this specification is automatically ruled out. The other characteristics have to do with the construction and use of the device.

Reflection of energy at the input of a standard attenuator can cause significant errors in its readings. Therefore, in order that all the incident energy may either be dissipated within the attenuator or transmitted through it, the input impedance must be accurately matched to the transmission line with which it is used. The output impedance must also be matched in order that the conditions necessary to make equation (2) valid will obtain. No exact specification of the degree of matching has been set forth, but a safe standard at the present time is to make the standing-wave ratio, due to reflections from a mismatch, less than 1.02:1.

Stability of the input and output impedances of a standard attenuator are important as well as stability of its at-

tenuation. Instabilities due to changes in atmospheric conditions are usually reversible: i.e., the attenuation or impedance is a direct function of the pressure, temperature or humidity, and follows them up or down. Aging, on the other hand, is an irreversible effect the rate of which may change with changes in atmospheric conditions. The importance, in the case of a primary standard, of minimizing instabilities due to handling and ordinary mechanical shock is obvious. Instabilities of all types in a standard attenuator should be small enough so that errors from this source are much smaller than errors from other sources.

The range of attenuation of a primary standard is not a characteristic of major importance, but in order to minimize the number of changes in the setup during a calibration, a range greater than that of any unknown component would be convenient.

If a primary standard is to be a useful device, its accuracy should be as great as can possibly be attained. The accuracy of an attenuator, as in the case of other standards, is a function of the degree of precision with which the device is made. A primary standard of attenuation must therefore be constructed with the greatest possible precision.

Frequency sensitivity of a primary standard attenuator is not a major problem, particularly in the case where it always operates at the same frequency. However, the change in attenuation and impedance with change in frequency should not be so great as to make the device unusable due to drift in the operating frequency. Such extreme frequency sensitivity

is not present in any of the attenuators that can be used as either primary or secondary standards.

4. Types of attenuators.

Attenuators fall into three general classes: dissipative types, power dividers and power reflection types. Not all of these classes are adaptable for use as primary standards of attenuation.

Dissipative attenuators can be made using several different kinds of materials, such as metallized glass, resistance cards and polyiron. Resistance cards, consisting of thin sheets of dielectric with a coating of resistive material on one side, are easily warped and are subject to atmospheric instability. Polyiron is a powdered iron held together by a binder. Its stability is not well known and it is easily damaged. Metallized glass, while it is fragile, does not absorb moisture and is quite stable with changes in temperature. Accurate attenuators, both fixed and variable, have been made using metallized glass.

Dissipative attenuators are easily matched to the transmission line and are not particularly frequency sensitive. However, they cannot be calibrated against fundamental dimensions, therefore this type is unsuitable for use as a primary standard.

Any device that diverts a portion of the energy flowing along a transmission line into a second transmission line is a power divider. If the remaining energy flowing in the first line is dissipated in a matched load and that portion

of the energy which was transferred to the second line is transmitted on to the rest of the circuit, the device functions as an attenuator. The most important examples of power dividers are directional couplers and bifurcated lines. In the former, a small portion of the energy in the main transmission line is coupled, usually through small holes, into a secondary line. For use as an attenuator, the main line is terminated in a matched load and the output of the secondary line becomes the output end of the attenuator.

A bifurcated line is one in which a thin partition is introduced normal to the electric field, which in effect divides the transmission line into two lines. As in the directional coupler, one of the smaller lines is terminated in a matched load and the other becomes the output of the attenuator.

Both of the above devices are essentially fixed in nature. Although either may be calibrated from its dimensions, the accuracy with which they can be constructed is not as great as the waveguide-be-low-cutoff attenuator (to be discussed below) because of a greater number of critical components and dimensions. In addition, the matched loads required by power-divider attenuators suffer from atmospheric instabilities.

A waveguide-below-cutoff is the only outstanding example of a power reflection attenuator. In this device, a coupling loop sets up an electromagnetic field in a waveguide whose dimensions are too small to propagate energy at the frequency concerned. A second coupling loop placed somewhere

along the waveguide will pick up energy proportional to the square of the magnetic field at that point, and since the field decays exponentially along the waveguide, the attenuation in decibels will be a linear function of the separation of the two loops.

The cutoff attenuator can be made quite rugged and its stability with changes in atmospheric conditions is very good. Since the input impedance for large values of loop separation is a pure reactance, the matching of a cutoff attenuator is an important problem. This can be done, however, with only a moderate amount of difficulty. The fact that the rate of change of attenuation with change in loop spacing is a function of one dimension of the waveguide makes the cutoff attenuator the most outstanding choice for a primary standard.

III. THEORY OF CUTOFF ATTENUATORS

Lord Rayleigh, in his paper published in 1897 [8] was probably the first to show that waves could be propagated in hollow pipes. Although he did not discuss the property of attenuation, he did clearly show what we now call the cutoff wavelength of a waveguide. The following paragraphs will show some of the theory as applied to waveguide-below-cutoff attenuators and will outline some of the major problems and their solutions.

1. Basic principles.

Above a certain critical frequency electromagnetic waves can be propagated along hollow conducting cylinders as a function of $e^{-\gamma z}$, where z is the distance along the axis of the cylinder and γ is a "propagation constant." (Ramo and Whinnery [11]) The propagation constant is given by

$$\gamma = \frac{2\pi}{\lambda_c} \sqrt{1 - \left(\lambda_c/\lambda\right)^2} \qquad (4)$$

where λ is the free-space wavelength of the wave in the cylinder and λ_c is the cutoff wavelength whose value depends on the dimensions of the cylinder. Above the critical frequency, the propagation constant is an imaginary number which represents a rate of change of the phase of the electromagnetic wave with distance along the cylinder. Below the critical frequency, the propagation constant is a real number which represents a rate of change of amplitude with distance along the cylinder. The latter property is the basis of a waveguide-below-cutoff attenuator.

A cutoff attenuator may be constructed from circular or rectangular waveguide and may be designed for either a TM or a TE mode. Circular waveguide has been used almost exclusively for microwave attenuators and also for i-f attenuators until recently. This popularity is due to the fact that an accurate cylindrical waveguide is more easily made than an accurate rectangular waveguide.

The cutoff wavelength for circular waveguide is given by

$$\lambda_c = \frac{2\pi r\sqrt{k_e}}{p_{mn}} \tag{5}$$

where r is the radius of the waveguide, k_e is the relative dielectric constant of the material within the waveguide, and p_{mn} is a dimensionless constant whose value depends upon the specific mode. Table I shows values of p_{mn} for several modes.

Table I. Values of p_{mn} in equation (5)

	TM modes			TE modes		
m \ n	1	2	3	1	2	3
0	2.405	5.520	8.654	3.832	7.016	10.17
1	3.832	7.016	10.173	1.841	5.33	8.54
2	5.135	8.417	11.620	3.05	6.71	9.97
3	6.379	9.760	13.017	4.20	8.02	11.35

For rectangular waveguide, the cutoff wavelength, for both TE and TM modes, is found from the equation

$$\lambda_c = \frac{2\sqrt{k_e}}{\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2}} \qquad (6)$$

where a and b are the wide and narrow inside dimensions of the waveguide, respectively. The quantities m and n have integral values and either may be zero for the TE modes, but not for the TM modes.

In either circular or rectangular waveguide, the attenuation constant, for frequencies such that $\lambda/\lambda_c > 1.05$, is given by

$$\alpha = \frac{2\pi}{\lambda_c}\sqrt{1 - \left(\frac{\lambda_c}{\lambda}\right)^2} \qquad (7)$$

This equation holds for either TE or TM modes. The importance of holding close tolerances in the dimensions of the waveguide is shown by the equation

$$\frac{d\alpha}{\alpha} = -\frac{1}{1 - \left(\frac{\lambda_c}{\lambda}\right)^2}\,\frac{dx}{x}$$

or, for $\lambda_c \ll \lambda$

$$\frac{d\alpha}{\alpha} = -\frac{dx}{x} \qquad (8)$$

where x is the radius of a circular waveguide or the wide dimension of a rectangular waveguide ($TE_{1,0}$ mode). This indicates that the percentage error in the attenuation constant equals the percentage error of the waveguide dimensions.

2. Some fundamental problems.

In the discussion above, the presence in the waveguide of only one mode was assumed and the equations are valid only when this condition obtains. Actually, the generation of a large number of different modes is inevitable in a practical attenuator, and since the presence of more than one mode causes a departure from the linear rate of attenuation, it is essential to suppress all but one mode. Suppression of these undesirable modes constitutes one of the major problems in the design of a cutoff attenuator. Each mode has a different rate of attenuation, as is shown in Table II. Thus, at a relatively large separation of the coupling loops, the mode having the lowest rate of attenuation will exist alone, the others being negligible by comparison. Much trouble from unwanted modes can be eliminated by exciting the mode with the lowest attenuation constant. This expedient insures that only the desired mode will be present for large coil separation. The other modes may still have appreciable relative amplitudes at close separation of the loops, however.

Table II. Ratio of attenuation constant of a mode to the smallest attenuation constant.

Rectangular Waveguide				Circular Waveguide	
	α/α min.				
Mode	a = b	a = 2b	a = 3b	Mode	α/α min.
$TE_{1,0}$	1.00	1.00	1.00	$TE_{1,1}$	1.00
$TE_{0,1}$	1.00	2.00	3.00	$TM_{0,1}$	1.31
$TE_{2,0}$	2.00	2.00	2.00	$TE_{2,1}$	1.66
$TE_{1,1}$, $TM_{1,1}$	1.41	2.24	3.16	$TE_{0,1}$, $TM_{1,1}$	2.08
$TE_{2,1}$, $TM_{2,1}$	2.24	2.83	3.60	$TE_{3,1}$	2.28
$TE_{3,0}$	3.00	3.00	3.00	$TM_{2,1}$	2.79
$TE_{3,1}$, $TM_{3,1}$	3.16	3.60	4.24	$TE_{1,2}$	2.90
$TE_{0,2}$	2.00	4.00	6.00	$TM_{0,2}$	3.00

Certain of the higher modes can be suppressed by means of symmetrical distribution of the exciting current. Unsymmetrical modes cannot be excited by symmetrical current distributions, just as a string plucked at its center will vibrate only at the fundamental frequency.

Another method for reducing higher modes is by means of mode filters. Such devices can be of several forms. One filter (Grantham and Freeman [5]) makes use of the fact that the wave impedance offered to a TM mode varies inversely as the relative dielectric constant of the material in the waveguide while the wave impedance of a TE mode is independent of the dielectric constant. A sheet of material having a high dielectric constant placed in the waveguide will therefore reflect TM modes and transmit TE modes. Another type of mode filter consists of a number of metallic strips or wires so

oriented that the surfaces are normal to the electric field of the desired mode. Any mode whose electric field in the waveguide is not normal to these metallic surfaces will be greatly attenuated by the filter. Thus, in a rectangular waveguide designed for the $TE_{1,0}$ mode, all modes except the $TE_{1,0}$, $TE_{2,0}$, $TE_{3,0}$, etc., can be eliminated effectively by means of a metal-strip filter. The $TE_{2,0}$, $TE_{3,0}$, etc., modes can be made insignificant by using a coupling coil which does not excite them in the waveguide.

Impedance matching of a cutoff attenuator is a difficult but not unsolvable problem. The difficulty is reduced considerably if the attenuator is to be used at only one frequency. For an i-f attenuator, the coupling coil can be combined in series with a condenser and a resistor so that the circuit is resonant at the frequency for which the attenuator was designed. The value of the resistance can then be chosen to make the input resistance of the attenuator the same as the characteristic impedance of the coaxial line with which it is to be used. By making the coil as large as is practicable, the Q of the circuit can be made high enough so that the insertion loss of the attenuator is reasonably low.

The effect of the finite conductivity of the waveguide walls on the accuracy of cutoff attenuators has been investigated by several people (Brown [1], Grantham and Freeman [5], Wheeler [13]). The analysis, which involves some rather complicated mathematics, will not be shown here but the results can be summarized as follows: For cutoff attenuators

operating in TM modes, the effect of finite conductivity of the waveguide walls is negligible. For attenuators operating in TE modes, the effect is to increase the critical dimension (the diameter of a circular waveguide or the wide dimension of a rectangular waveguide) by an amount equal to the depth of penetration. This error may be significant for precision attenuators operating at low frequencies.

IV. THE SPERRY PRECISION CUTOFF ATTENUATOR

1. Specifications and design data.

The cutoff attenuator to be described herein is the result of a need for a precision standard of attenuation by the Microwaves Standards Section of the Sperry Gyroscope Company. The specifications set forth by the Standards Section were quite broad and consisted of the following items:

a.	Operating frequency:	30 mc
b.	Rate of attenuation:	20 db/inch
c.	Reading accuracy:	.001 db or better
d.	Variable range of attenuation:	110 db

A similar device is under construction at the National Bureau of Standards, but operates at 20 megacycles.

In order to provide a lesser problem insofar as mode suppression is concerned, a rectangular waveguide operating in the $TE_{1,0}$ mode was chosen. From equation (6), the cutoff wavelength for the $TE_{1,0}$ mode is found to be twice the wide dimension of the waveguide. Substituting this value of λ_c in equation (7), we find

$$\alpha = \frac{\pi}{a}\sqrt{1 - \frac{4a^2}{\lambda^2}} \tag{9}$$

from which

$$a = \frac{\pi}{\sqrt{\alpha^2 + \frac{4\pi^2}{\lambda^2}}} \tag{10}$$

When the specified values for α and λ are substituted into Equation (10), the required width of the waveguide is found to be 1.36434 inches. In order to provide maximum accuracy of the attenuation constant, this dimension must be maintained within as close a tolerance as is practicable. The narrow dimension of the waveguide is not so important but it should be made half the wide dimension, or less, to insure rapid attenuation of higher modes that might inadvertently be excited. (See Table II).

Proper design of the coupling coil also aids in the suppression of the unwanted modes. The coils should be of such form that only the $TE_{1,0}$ mode will be excited. This end can be accomplished only if the current distribution is perfectly symmetrical with respect to a cross-section of the waveguide. Since perfect symmetry is not possible in practical coils at 30 megacycles, some of the higher modes will be excited at low levels, making necessary the use of a mode filter of the parallel metal-strip type. The use of these three methods: ratio of wide to narrow waveguide dimensions of 2:1 or more, symmetrical excitation, and the mode filter should effectively eliminate trouble from unwanted modes.

2. Description and experimental performance.

The Sperry precision cutoff attenuator consists of a section of rectangular waveguide mounted on a carriage which rests on four ball bearings running on an accurately machined rail, similar to a lathe bed. The input coupling coil is wound from number 26 bare tinned wire on a form which is mounted on the end of a length of rigid coaxial transmission

line extending into the waveguide through a hole in the end of the carriage. The other end of the coaxial line is mounted on a bracket at one end of the rail and is terminated in a Type N coaxial fitting. The waveguide is moved with respect to the stationary input coil. The output coil is wound on a similar form mounted on the support which holds the right-hand end of the waveguide onto the carriage. The output coil is also connected to a Type N coaxial fitting. The total motion of the carriage is about 5.7 inches, the amount of motion being read on a micrometer head calibrated in ten-thousandths of an inch. The one-inch range of the micrometer is extended in one-inch increments by means of spacing rods that are accurate to 0.0001 inch.

The photograph, Figure 3. shows the completely assembled attenuator. Figure 4 is a photograph of the attenuator with the waveguide removed showing the input and output coil assemblies. The drawings, Figures 5 and 6, show a section through the input end of the waveguide, and a detail of the input coil assembly, respectively.

The waveguide section is of silver and copper electroformed on an invar mandrel. The inside dimensions of the waveguide, 0.6800 inch by 1.3644 inches, are accurate within ±0.0002 inch. The outside of the waveguide is machined to 1.000 inch by 1.750 inches. A metal-strip mode filter is located in the waveguide near the output coil. The filter consists of 15 strips of phosphor bronze, each 0.125 inch wide by 0.015 inch thick, pressed into equally spaced parallel slots in a block of bakelite 0.250 inch thick. The ends

of the strips are soldered to flat phosphor bronze springs which contact the narrow sides of the waveguide.

A real test of the Sperry precision attenuator is not possible at the time of this writing, since it is, to the best of the writer's knowledge, the only intermediate-frequency attenuator presently available which is capable of accuracies on the order of five-thousandths of a decibel. In order to check for gross errors, such as might result from r-f leakage from the sliding joint where the coaxial line enters the waveguide, the precision attenuator was tested against one of the Sperry Gyroscope Company's Model 127A cutoff attenuators whose accuracy is within ± 0.1 decibel. A block diagram of the test setup is shown in Figure 7.

The test was run in two steps: the first part without the pre-amplifier ahead of the Model 127A attenuator. Instead, the pre-amplifier was replaced by another Model 127A attenuator, Serial 42, which had previously been calibrated against the "standard" Model 127A attenuator. The extra attenuator was maintained at a fixed value to extend the range of the "standard" Model 127A attenuator. As the "standard" attenuator dial reading was decreased in 5 decibel steps, the attenuation of the precision attenuator was increased to maintain a constant power level at the detector. After the coil separation of the precision attenuator had been increased by about 3 inches (60 db increase in attenuation), it was necessary to replace the extra attenuator by the pre-amplifier in order to increase the sensitivity of the amplifier-detector

system (Sperry's 30mc receiver 9090062, number 1, including the standard Model 127A attenuator). The test was continued, using the pre-amplifier, until the precision attenuator read 4.75 inches (95 db, plus 20 db insertion loss), at which point the signal at the input of the pre-amplifier was submerged in the amplifier noise. A graph showing the test results is shown in Figure 8.

The maximum error of the precision attenuator, for increments of 0.2500 inch, over the range from zero to 4.75 inches was 0.0016 inch, or 0.032 decibel. This is well within the possible experimental error and indicates that the precision attenuator has a linear attenuation characteristic with a rate of 20 decibels per inch, as nearly as it is possible to determine at the present time.

When other attenuators with accuracies comparable to the Sperry precision cutoff attenuator become available, further tests are planned. In particular, a check against the National Bureau of Standards cutoff attenuator is anticipated in the near future.

V. CONCLUSIONS

A waveguide-below-cutoff type of attenuator has been shown to be the only outstanding choice for use as a primary standard of attenuation, because its calibration can be calculated from fundamental dimensions. A device whose accuracy is as good as the Sperry cutoff attenuator promises to be, will not only make possible more precise measurements of attenuation, but also will establish a highly accurate value for the decibel itself as a unit of measurement. Although the decibel has been defined quite rigidly by equation (2), differences in techniques of measurement have resulted in the adoption of different standards of attenuation by various laboratories. The use of a precision wave-guide-below-cutoff attenuator as a primary standard, because it can be calibrated from fundamental dimensions, will eliminate the ambiguity on the size of the decibel.

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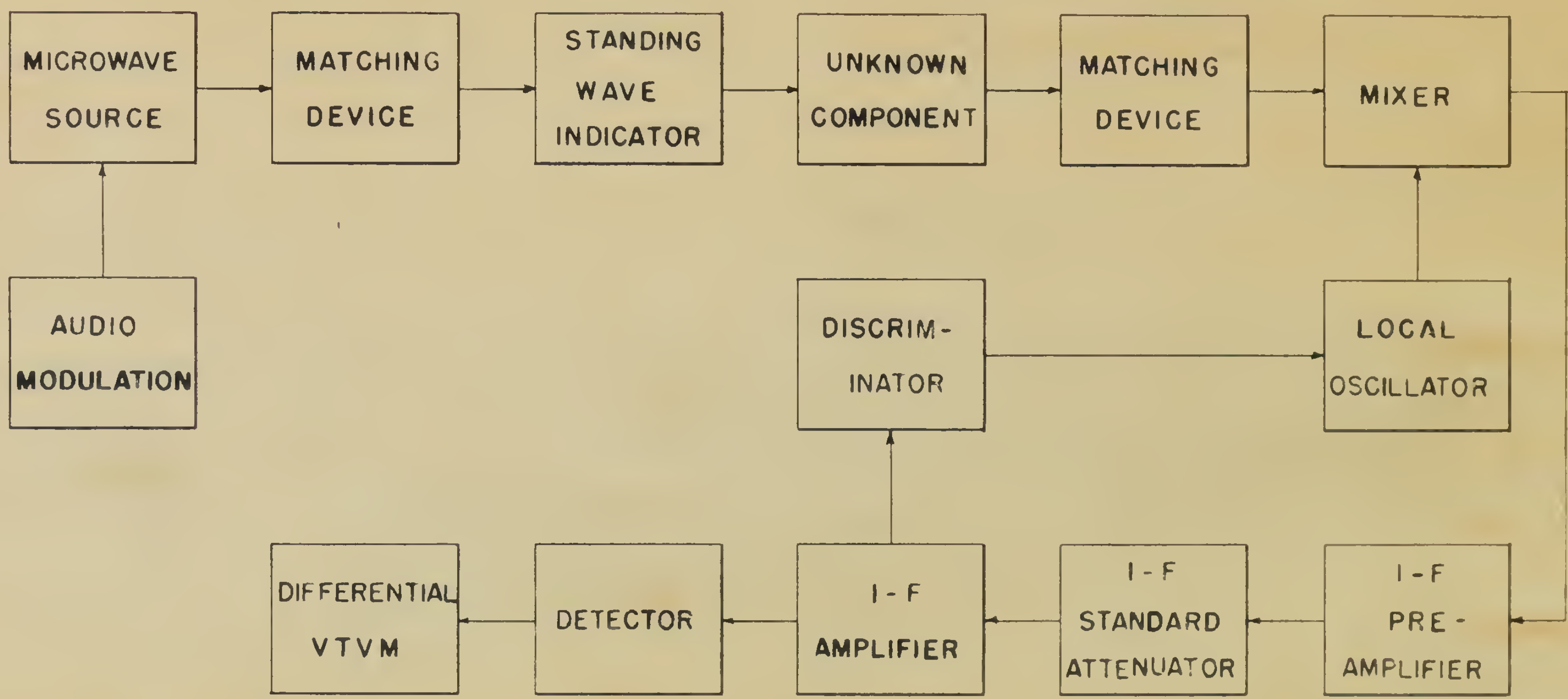
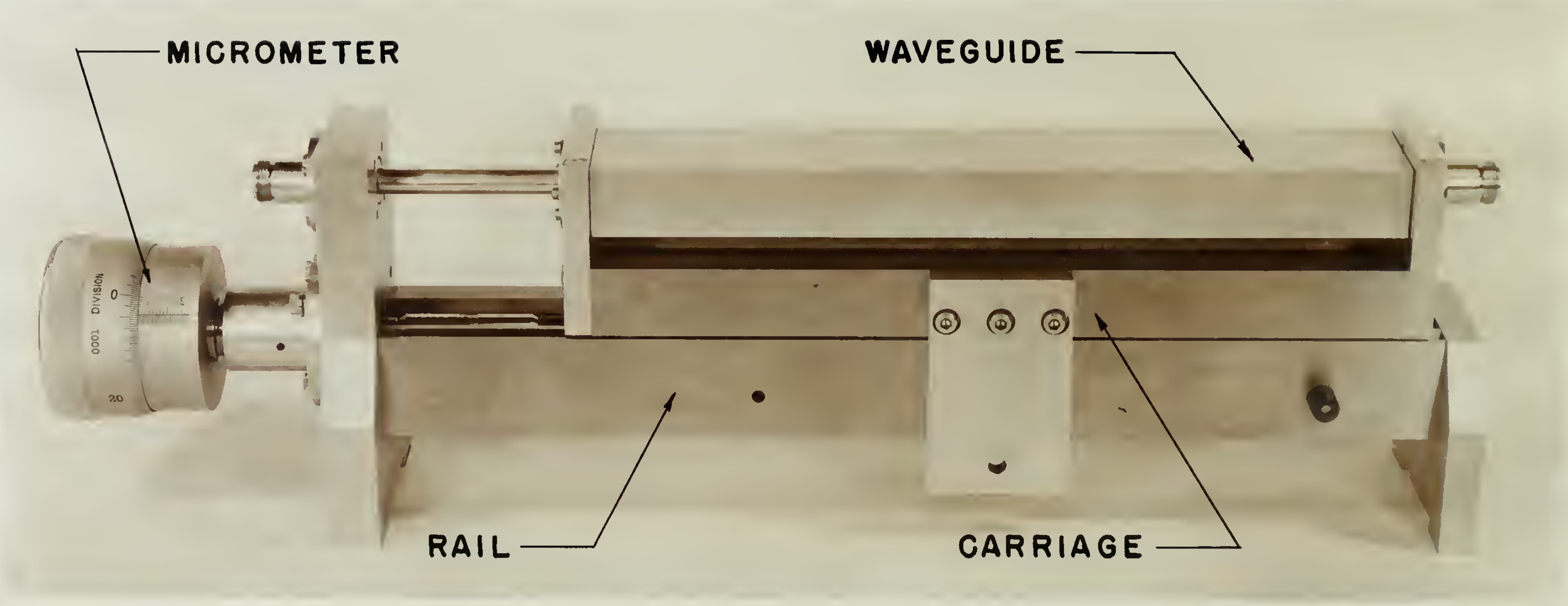


AFC HETERODYNE METHOD

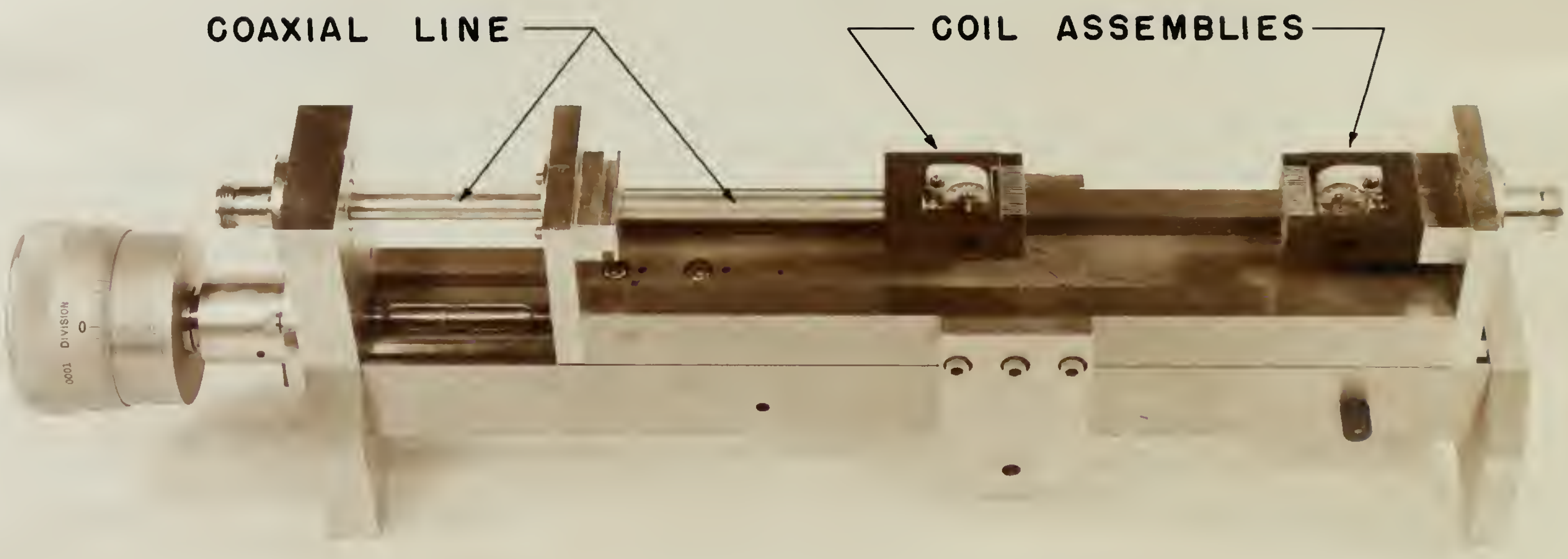
BLOCK DIAGRAM

Figure 2



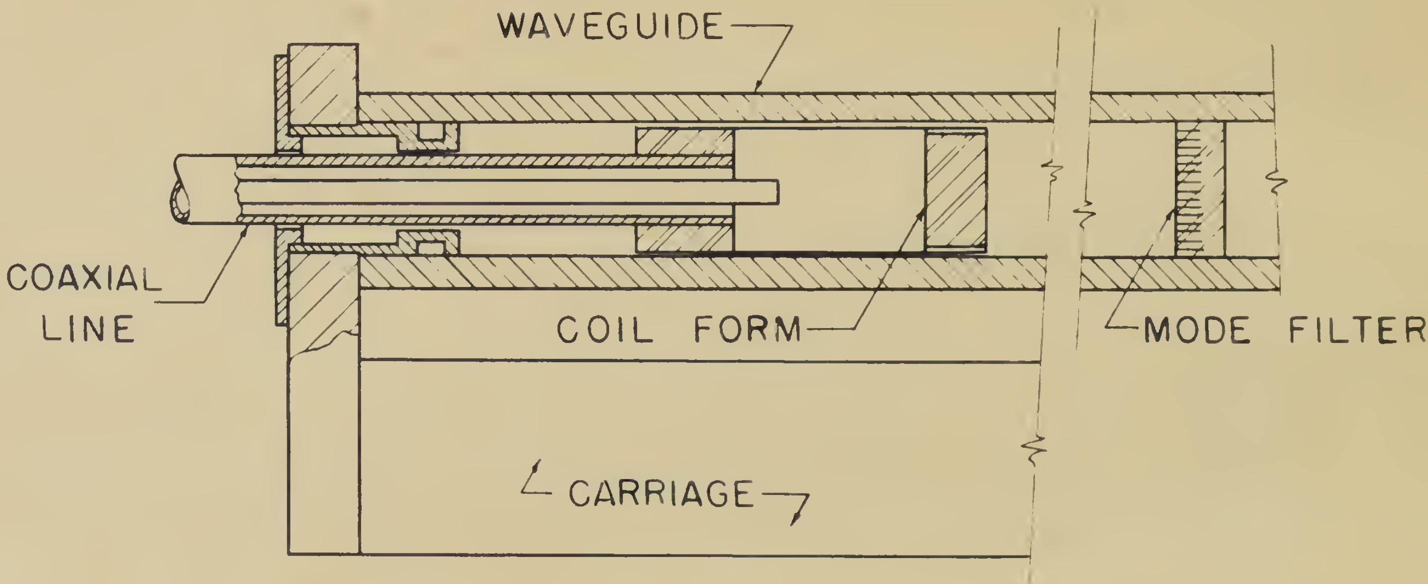
SPERRY CUTOFF ATTENUATOR

Figure 3



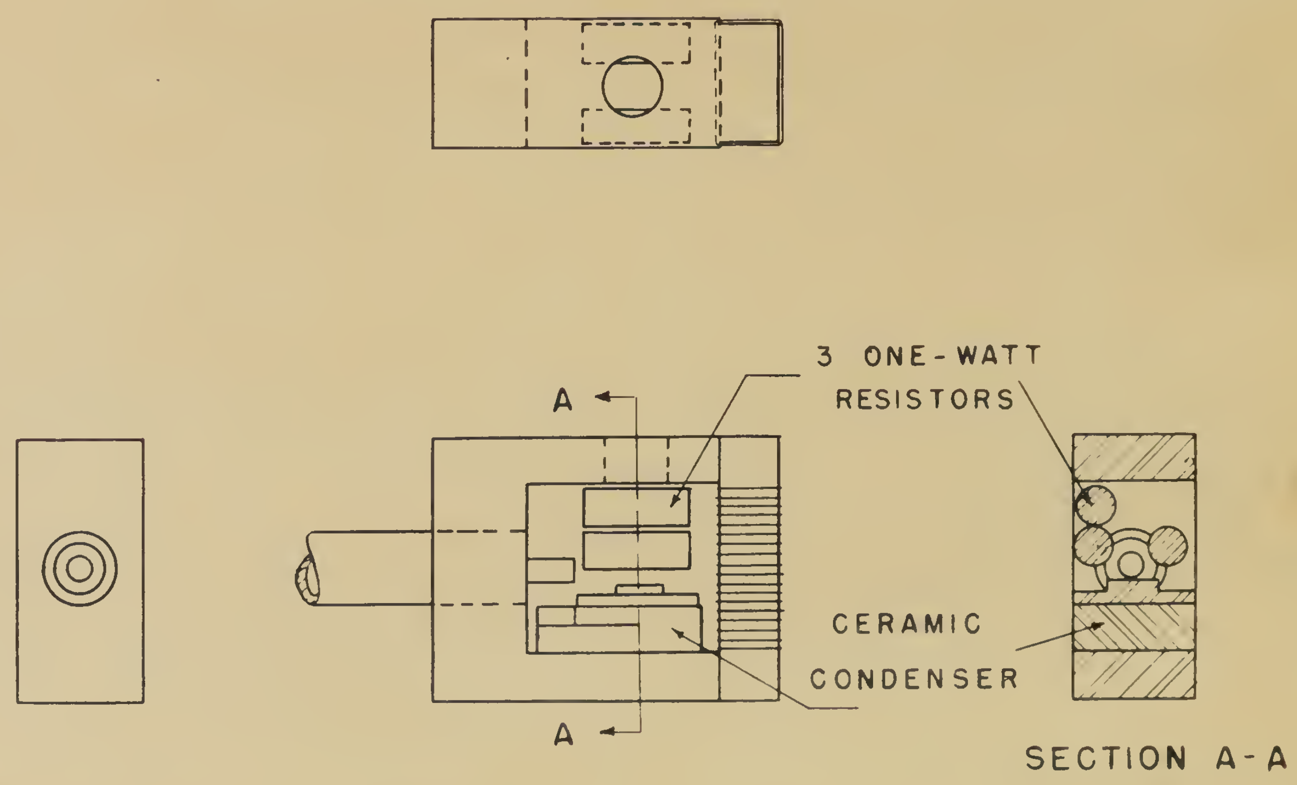
ATTENUATOR WITH WAVEGUIDE REMOVED

Figure 4



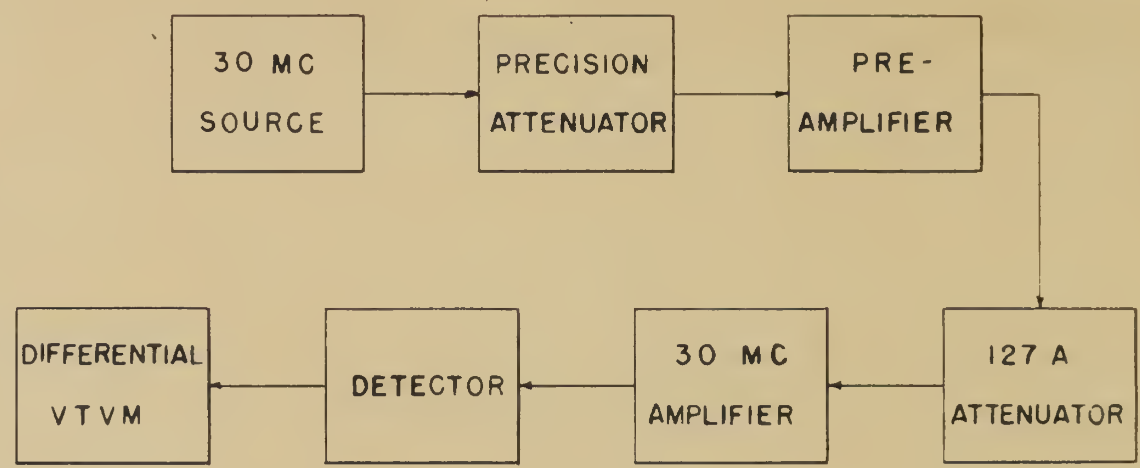
SECTION OF
INPUT END OF WAVEGUIDE

Figure 5



INPUT COUPLING COIL ASSEMBLY

Figure 6



TEST SET-UP

BLOCK DIAGRAM

Figure 7

Figure 8. Graph of Typical Test Results

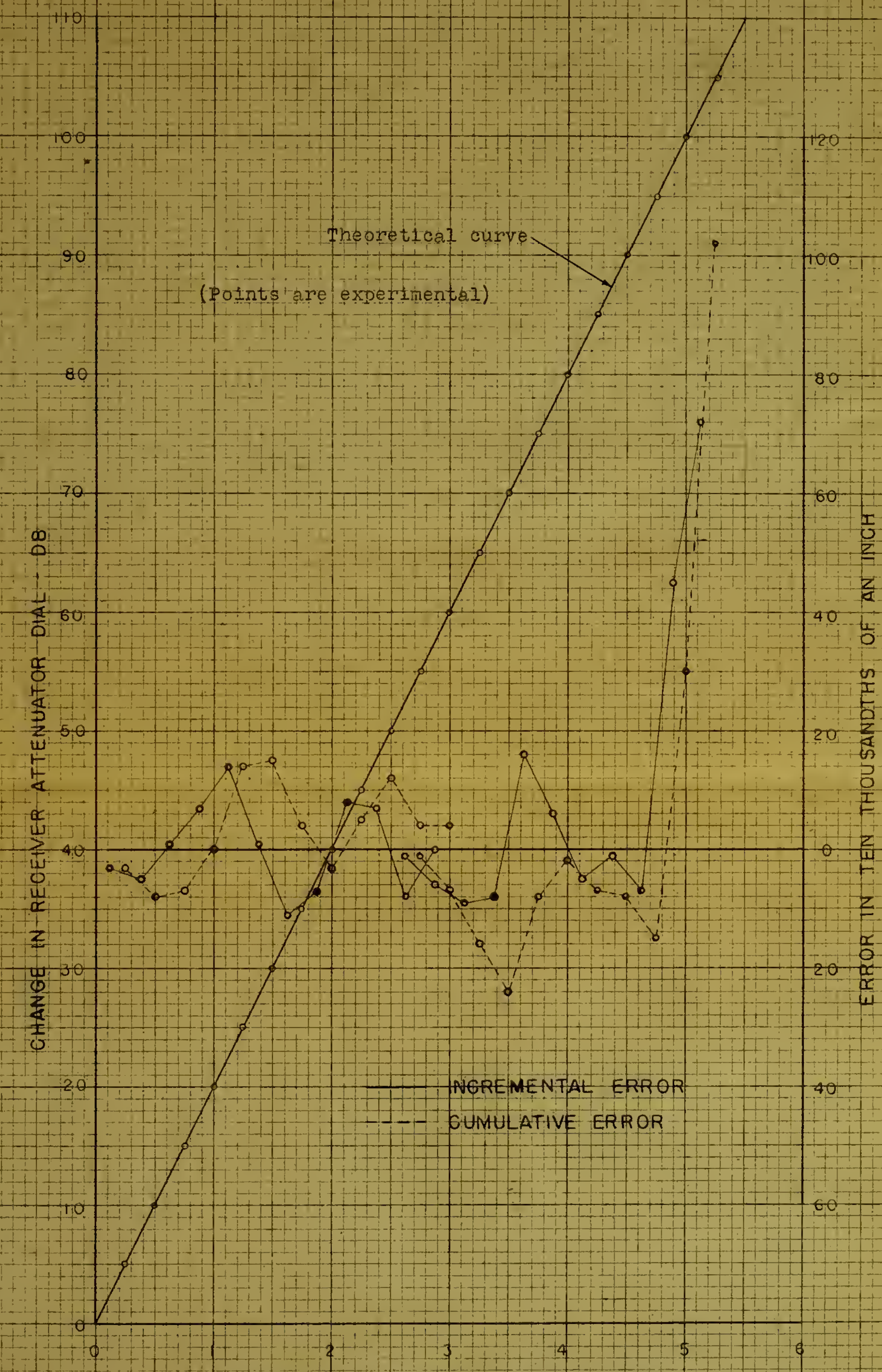

Theoretical curve
(Points are experimental)
CHANGE IN RECEIVER ATTENUATOR DIAL - DB
ERROR IN TEN THOUSANDTHS OF AN INCH
INCREMENTAL ERROR
CUMULATIVE ERROR
PRECISION ATTENUATOR DIAL - INCHES
110
100
90
80
70
60
50
40
30
20
10
0
120
100
80
60
40
20
0
20
40
60
0
1
2
3
4
5
6

Figure 8